

Kepler White paper:

Ensemble ASteroseismoLOGY of the Y oung Open Cluster NGC 2244 (EASILY)

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Abstract

Our goal is to perform in-depth ensemble asteroseismology of the young (age less than 6 million years) open cluster NGC 2244 with the 2-wheel *Kepler* mission. While the nominal *Kepler* mission already implied a revolution in stellar physics for solar-type stars and red giants, it was not possible to perform asteroseismic studies of massive OB stars because such targets were carefully avoided in the FoV in order not to disturb the exoplanet hunting. Now is an excellent time to fill this hole in mission capacity and to focus on the metal factories of the Universe, for which stellar evolution theory is least adequate.

Our white paper aims to remedy major shortcomings in the theory of stellar structure and evolution of the most massive stars by focusing on a large ensemble of stars in a carefully selected young open cluster. Cluster asteroseismology of very young stars such as those of NGC 2244 has the major advantage that all cluster stars have similar age, distance and initial chemical composition, implying drastic restrictions for the stellar modeling compared to asteroseismology of single isolated stars with very different ages and metallicities.

Our study requires long-term photometric measurements of stars with visual magnitude ranging from 6.5 to 15 in a large FoV with a precision better than ~ 30 ppm for the brightest cluster members (magnitude below 9) up to ~ 500 ppm for the fainter ones, which is well achievable with the 2-Wheel *Kepler* mission, in combination with high-precision high-resolution spectroscopy and spectro-polarimetry of the brightest pulsating cluster members. These ground-based spectroscopic data will be assembled with the HERMES and CORALIE spectrographs attached to the twin 1.2 m Mercator and Euler telescopes at the Observatories

of La Palma, Canary Islands and La Silla, Chile, respectively, as well as with the spectro-polarimetric NARVAL instrument attached to the 2 m Bernard Lyot Telescope at the Pic du Midi in the French Pyrenees, to which the scientists in the present consortium have guaranteed access.



Figure 1: Image of the open cluster NGC 2244 on the sky.

Scientific Context and State-of-the-Art

Stellar evolution theory is most uncertain for massive stars, where core convective overshooting, internal differential rotation, magnetic fields, and transport of angular momentum and of chemical species are all important yet poorly understood physical ingredients. Moreover, these phenomena are of relevance during many of the evolutionary phases, from the star formation until the very late stages. While parametrised descriptions have been used to include them in stellar evolution codes of single and binary stars, the theoretical predictions remain essentially uncalibrated by high-precision data so far. Quite crucially, the introduction of these physical processes has a major impact on the outcome of the theory. Moreover, the predictions for the evolutionary properties of massive OB stars, and by implication also the theoretical predictions for supernova progenitors, galaxies, and chemical enrichment of the Universe as a whole, are considerably different for codes that have been developed by independent teams. We cannot but conclude that theoretical stellar evolution models of massive stars are very uncertain while, at the same time, these models are used as the

building blocks of much of modern astrophysics. Here, we focus on the earliest stages of stellar evolution of massive stars.



Asteroseismology of the four open clusters in the field-of-view of the nominal *Kepler* mission, based on solar-like oscillations in red giants is successful and progressing fast (Stello et al. 2011, Miglio et al. 2012, Corsaro et al. 2012). These studies have the potential to lead to seismic constraints on mass loss on the red giant branch for clusters of different metallicity and age covering a few to several giga years. *CoRoT nor Kepler were able to gather suitable data for ensemble modeling of young open clusters of only a few million years old, based on OB-type pulsators. This is the purpose of our proposal.*

Pulsating OB stars in or past the core-hydrogen burning stage reveal low-order pressure and gravity modes as well as high-order gravity modes excited by various mechanisms, making it necessary to observe them with a time base of months in order to resolve a sufficient number of modes needed to perform seismic modeling. Large ground-based multitechnique campaigns dedicated to pulsating B stars had been performed prior to the CoRoT launch in 2006 and have led to the derivation of the core overshoot parameter and of the ratio of the core to envelope rotation for a few targets (Aerts et al. 2003, 2011; Briquet et al. 2007; Dziembowski & Pamyatnykh 2008, among others). Despite large efforts, daily aliases remained an observational difficulty, because these stars often have (beat) periods of the order of days and the modelling had to be restricted to only a few identified modes.

Crucial steps ahead were achieved in the assembly and interpretation of seismic data of various B and Be stars with a time base of five months and a sampling of 32 seconds with the CoRoT mission. In addition to the derivation of the core overshoot parameter for a few more stars, this revealed a diversity in stellar variability of massive stars with amplitude below 0.1 mmag that was unanticipated from ground-based data (Neiner et al. 2009, Huat et al. 2009, Gutiérrez-Soto et al. 2009; Diago et al. 2009; Degroote et al. 2009, 2010a, 2012; Pápics et al. 2011, 2012). The duty cycle of the data solved the aliasing problems occurring in ground-based data and these recent studies led to compatibility checks for current stellar models (Aerts et al. 2011), to the derivation of the extent of core overshoot and of extra near-core inhomogeneous near-core mixing (Degroote et al. 2010b) and quite often to the failure to explain the excitation of detected modes from present-day pulsation theory. It also pointed out that the pulsations of Be stars are in need of better theoretical interpretation which can handle the complexity of the frequency spectrum due to the deformation and fast rotation of those stars (Neiner et al. 2012).

To bring a new dimension in this research, we need observations with a high duty cycle and with a time base of at least half a year for an ensemble of massive stars with similar constraints on metallicity and age, in such a way that we can detect rotational splitting of the pulsation modes of numerous cluster stars, including the slowest rotators.

The limits of what can be done from the ground were explored by Saesen et al. (2010), who organised a huge ground-based 2.5-year multicolour photometric multisite campaign focusing on the young open cluster NGC 884, involving 12 observatories. This study revealed 36 multi-periodic B-stars and 39 mono-periodic B-stars, but, despite immense efforts, suffered severely from daily aliasing and low duty cycles, as well as being limited to light curves with a precision of 5.7 mmag in the *V* filter, 6.9 mmag in *B*, 5.0 mmag in *I* and 5.3 mmag in *U* for the brightest cluster members. From frequency analysis and empirical mode identification from amplitude ratios of five cluster members, Saesen et al. (2013) managed to deduce a

seismic age for the cluster in agreement with the one deduced from an eclipsing binary cluster member. Their study was a proof-of-concept for the power of asteroseismic modeling of a young open cluster, should data of higher duty cycle and with a factor ten better precision become available. At the same time, *this study made it obvious that progress cannot be made efficiently from ground-based efforts because we need better detection capabilities for the pulsation modes, typically at the level of 0.1 to 0.5 mmag.*

A similar conclusion holds for young stars in their pre-main-sequence (pre-MS) phase: progress only started efficiently by monitoring members of young open clusters with the MOST and CoRoT satellites, in combination with ground-based spectroscopy and in some cases X-ray measurements (e.g., Zwintz et al. 2011, 2013a,b). Variability at the level of 0.5 mmag or less occurs in a diversity of pre-MS stars while theoretical instability computations fail to explain the detected modes for various stars.

We conclude that high-precision ensemble seismic modeling of the most massive stars and of stellar objects near the birthline is unavailable at present. With this project, we will provide it with the 2-Wheel *Kepler* mission for a carefully selected young open cluster containing confirmed pulsators in the appropriate classes among its members.

The main target: the young open cluster NGC 2244

The very young open cluster NGC 2244 (Fig. 1; RA2000 = 06:31:55, DEC2000 = 04:56:30) belongs to the Mon OB2 association and is situated at a distance of 1.6 ± 0.2 kpc. Its age is estimated to be between one and six million years (Bonatto & Bica 2009). Its diameter is some 30 arcminutes and its stellar density is suitable for observations with *Kepler* in the sense that crowding is not a major limitation (Fig. 2). Several members of this bright cluster have also been studied carefully in UV-wavelengths and in X-rays, which will allow us to get the basic stellar properties from well-determined spectral energy distributions. Such multiwavelength studies revealed a discrepancy between spectroscopic and evolutionary masses of cluster members with masses below $25 M_{\odot}$ (Martins et al. 2012).

Chemical abundance analyses of hot massive cluster members (Vranks et al. 1997; Pavloski & Hensberge 2005; Martins et al. 2012) agree very well with the present-day standard abundances of $X = 0.715$ and $Z = 0.014$ determined by Przybilla et al. (2008). Hence, pulsations are expected all along the main sequence of NGC 2244 (Miglio et al. 2007). We shall pay specific attention to the occurrence or absence of pulsations in stars with spectral type near B9 to A0, where new pulsators were only recently found from ground-based cluster studies (Mowlavi et al. 2013), while such periodic variability is not predicted from theoretical models.

A major reason why we selected NGC 2244 as the best target for our scientific aims is the fact that four of its O-type stars have already been monitored by CoRoT during a short run lasting 34 days. This revealed a diversity of causes for the detected stellar variability:

- The slowly-rotating O9V member HD 46202 (visual magnitude of 8.2) turned out to be a “classical” β Cep-type pulsator, the one with the highest mass known so far (Briquet et al. 2011). Its pulsation frequencies occur near $60 \mu\text{Hz}$ and have amplitudes between 30 and 100 ppm. While its few detected zonal modes could be well modeled by current stellar models, none of the observed modes are predicted to be excited and a discrepancy was found between the spectroscopic and seismic $\log g$.

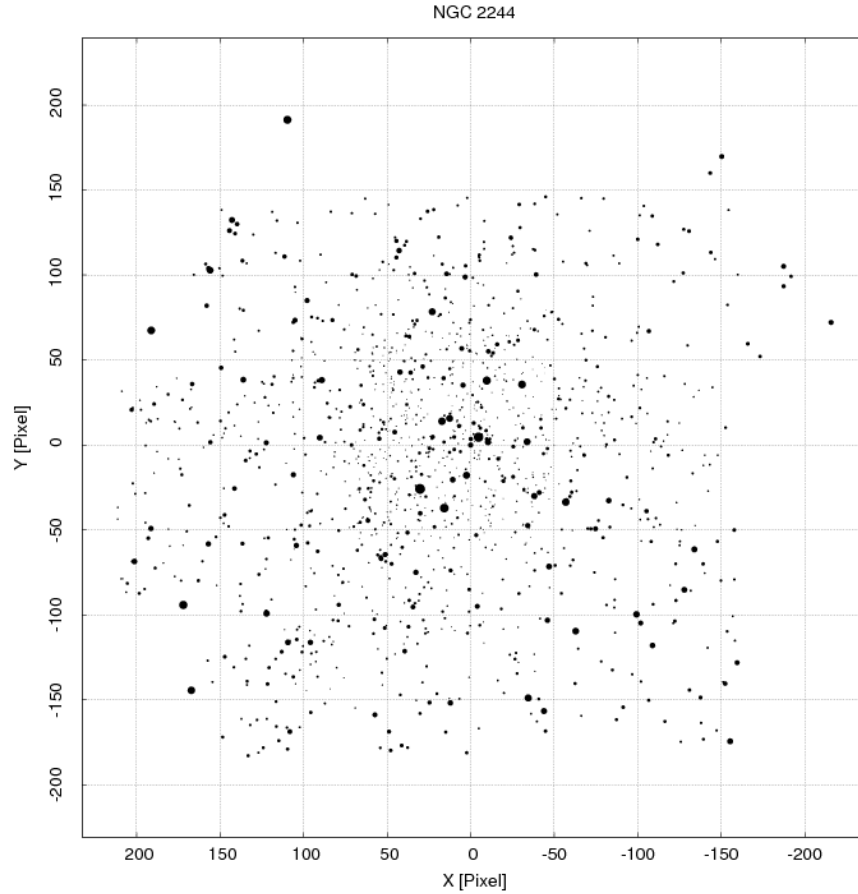


Figure 2: Cluster map obtained from the WEBDA data base of open clusters. The scale is such that 6.00 units correspond with one arcminute (source: Massey et al. 1995).

Rotational splitting was not detected in the time series, due to a too short time base resulting in too poor frequency resolution.

- Quite unexpectedly, stochastic oscillations with frequencies between 30 and $80\mu\text{Hz}$ and amplitudes between 20 and 50 ppm with Lorentzian profiles similar to those found in solar-type stars, were found in the primary of the bright spectroscopic cluster binary HD 46149 (visual magnitude of 7.6, Degroote et al. 2010a). Just like HD 46202, this massive pulsator is also a slow rotator. Its stochastic pulsation modes seem to point out that this star must somehow sustain a considerable outer convective layer, which might create magnetic activity close to the stellar surface (Cantiello & Braithwaite 2011). Further investigation is needed to interpret the observed variability; rotational splitting was not detected so far.
- The most massive cluster members HD 46223 (visual magnitude of 7.2) and HD 46150 (visual magnitude of 6.8) are moderate to fast rotators and turned out to be variable with an excess power at low frequencies and amplitude near mmag, connected with a yet unknown stochastic process (Blomme et al. 2011). It is noteworthy that similar behaviour was recently identified in the ultra-bright *Kepler* GO eclipsing binary B1III target V380 Cygni (Tkachenko et al. 2012).

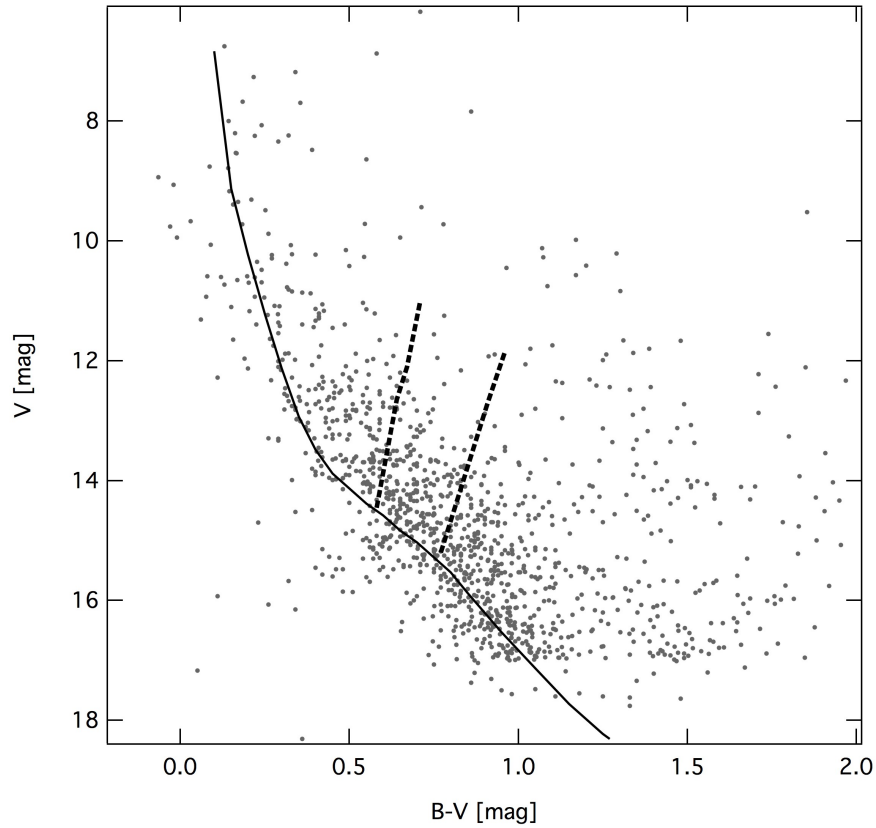


Figure 3: Colour-magnitude diagram of all the known members of the open cluster NGC 2244. The full line indicates the zero-age-main-sequence while the two dotted lines represent the blue and red border of the classical instability strip.

In addition, gravity-mode pulsations were found in two additional relatively bright cluster members with spectral type mid-B (visual magnitudes near 10 and 11) from a 21-day MOST campaign (Gruber et al. 2012). Modeling was not possible due to lack of frequency resolution and mode identification, as it concerned very few isolated frequency peaks, without any signature of rotational splitting.

Ensemble seismic modeling of these massive cluster members, imposing a single initial composition and age as in Saesen et al. (2013) was hitherto impossible due to too limited frequency resolution and lack of mode identification. However, these preliminary findings show that NGC 2244 is ideally suited as target for our scientific goals.

All these previously gathered space photometric data are available to the proposers of this white paper and *will allow us to calibrate the new data on NGC 2244 to be assembled with 2-Wheel Kepler*, with a guarantee to detect time-resolved pulsations in various of the cluster members.

We aim to observe the ~ 700 cluster members brighter than visual magnitude 15. This sample includes numerous pre-MS stars of spectral types B and A as well as all the core-hydrogen burning stars of type O and B. This will allow us to get the very first complete picture of all the variable stars considerably more massive than the Sun in an ultra-young cluster and study evolutionary and pulsational effects from the star formation process up to the exhaustion of core-hydrogen burning for single and binary cluster members. Long-term high-precision photometry revealing the variability of young and active stellar objects still embedded partly in their circumstellar birth cloud will be addressed as well and confronted with existing low-resolution data at infra red wavelengths. A search for hot Jupiters and other planets around A-type stars in this young cluster with solar metallicity will be undertaken as well.

Observing strategy

The cluster members have a visual magnitude range between 6.5 and 17 and cover OBAF stars in the core-hydrogen burning phase as well as lots of pre-MS stars (with visual magnitude as of 12 or fainter). The colour-magnitude diagram shown in Fig. 3 shows the breath in types of stars in the cluster. The twenty-ish brightest OB stars need to be observed with a precision of some tens of ppm. They will lead to saturated pixels, but experience with the design and observations through customized masks for such bright targets in the nominal *Kepler* mission has proven to be very successful (Metcalf et al. 2012, Tkachenko et al. 2012). We thus propose to devise specific and very large elongated masks for those bright cluster members which are brighter than the saturation limit, compensating also for the drift and jitter motion. Adapted masks should thus involve thousands of pixels per bright cluster star, but this is still very modest compared to the more than five million available pixels.

From the *Call for white papers document* we deduce that 2-Wheel *Kepler* can point to an accuracy of about one arcsec, undergoes a drift of 120 arcsec/day and maintains a one arcsec jitter about the drift line for less than or equal to a maximum of 4 days, after which a repointing is necessary. From Fig. 2, we derived the minimum requirement to limit the acceptable drift to 1 arcminute, i.e., we propose to repoint every 12 hours. In this way, we avoid that the photons of various cluster members get mixed into the masks of neighbouring stars while on the other hand we do not interfere with the periods of the pressure modes (typically between 3 and 7 hours). The gravity modes have periods typically between one and three days, which is too long to monitor completely without repointing. Half a day seems to be the best compromise to leave the cluster stars in their masks while having sufficiently long time strings to perform *a posteriori* corrections for inter- and intrapixel variability. For the latter, we shall rely on the methods for jitter (Drummond et al. 2006) and background (Drummond et al. 2007) correction algorithms developed previously in the Leuven team for the CoRoT mission. This software shall be adapted to the case of the 2-Wheel *Kepler* operations.

An alternative operational mode would be to consider very many small adjacent masks. Each target would then go out of a particular mask and go straight into the next mask, etc. Appropriate flux book-keeping might allow to achieve one merged time series per target, which would avoid having lots of stars in one large elongated mask. It is to be investigated with the Kepler instrument team whether this is an acceptable mode of operation; if so then repointing at a different pace than requested above could be considered.

Previous experience with asteroseismology of B pulsators from ground-based multisite campaigns and from CoRoT data (e.g., Degroote et al. 2012) has shown that rotational splitting in slowly rotating OB

pulsators as some stars in NGC 2244 requires a frequency resolution of at least $0.06\mu\text{Hz}$. **This is an essential requirement, because successful seismic modeling demands unambiguous identification of the pulsation modes and high-precision frequency matching. A shorter time base will only lead to the discovery and classification of the variables in the cluster but will not allow seismic modeling capable of improving the interior physics of the stars, while this is our global aim. Thus, we request continuous monitoring of the field centered on NGC 2244 during six months.**

Should our white paper be accepted, then we shall organise simultaneous ground-based time-resolved spectroscopic and spectro-polarimetric campaigns with the twin 1.2m Mercator & Euler telescopes, and with the 2m Bernard Lyot telescope. The proposing team has permanent access to these three facilities. This will be appropriate for the brightest cluster members only (visual magnitude up to 9). For the fainter cluster members, we shall apply for time on larger aperture telescopes (polarimetric mode of the 3.6m telescope (HARPSpol) and VLT (high-resolution multifiber UVES/FLAMES spectrograph) available at ESO through the normal biannual competition for which the current team members were very successful the past years.

Priority should be given to devise the optimal masks for all the ~ 700 NGC 2244 cluster members brighter than magnitude 15, which can be observed with a precision better than ~ 500 ppm. Using all 5.44 million pixels takes about 12 minutes of time to readout and store on board. Even though such slow readout is an acceptable cadence for our science case, it is better to adopt a higher read-out cadence for less pixels, in order to optimally resolve the pulsational behaviour of all the cluster members. Thus, we adopt the strategy to read out all the pixels of all the cluster members with a cadence of 5 minutes, keeping many of the pixels available for simultaneous complementary science, several of which can be read out in short cadence.

Concrete Workplan and Timeline

Let us denote the start of the 6-months monitoring with 2-Wheel *Kepler* observations by T_0 . The timeline of our project is as follows:

1. $[T_0, T_0+6 \text{ months}]$: gathering of ground-based spectroscopy and spectro-polarimetry. Computation of suitable grids of evolutionary models with the MESA code (Paxton et al. 2011) and with the accompanying non-adiabatic pulsation code GYRE (Townsend & Teitler 2013).
2. $[T_0+6 \text{ months}, T_0+12 \text{ months}]$: calibration and analysis of *Kepler* photometry and ground-based data. Classification of all the variables in NGC 2244 and selection of all the pulsators. First publication on the data and variables.
3. $[T_0+12 \text{ months}, T_0+18 \text{ months}]$: binary light curve and radial-velocity modeling; identification of the wavenumbers (ℓ, m) of all the detected pulsation frequencies. Second publication on the pulsators and their modes.
4. $[T_0+18 \text{ months}, T_0+24 \text{ months}]$: ensemble modeling of the entire cluster. Publication of the final modeling results.

All the necessary methodology and software for these tasks is available at the host institutes of the proposers. We refer to the Reference list below as a witness of the experience of the current proposers in this exciting research field.

Complementary Science Cases

Our proposal is focused on NGC 2244 as **the main target**. However, the *Kepler* FoV is about 100 square degrees and lots of additional scientifically valid targets in or near the Galactic disc will come for free within this FoV, while centering it on the main cluster target. Should our white paper be selected for observations, we suggest to make a call to the community to propose additional targets and operation modes in terms of left-over masks and integration times, with the coordinate information of NGC 2244.

It is noteworthy that the FoV can be chosen such as to have overlap with one of the short-run pointings done by CoRoT and that a classification of the variability of faint CoRoT stars was produced by members of our current team; all those CoRoT data are available to us (Debusscher et al. 2011). In general, the Leuven classification software is available for any of the 2-wheel *Kepler* pointings to optimize the scientific output of the mission.

In this way, the present white paper will become a community proposal with the prime science case of NGC 2244 and numerous additional science cases complementary to the one we propose here. Surely, the *Kepler* community will [EASILY](#) come up with brilliant ideas for the free pixels in the surrounding area near NGC 2244.

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